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SATELLITE ALTIMETRY

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ABSTRACT

Satellite radar altimeters are being considered by several scientists as an instrumentation for the study of planet topography. A review is presented of the basic satellite radar altimeter requirements for the study of topography, sea condition and orbit determination is presented. Methods of implementing these basic requirements for various types of topography are included. State-of-the-art techniques are also included along with some technological considerations which may require space application development programs.

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SUMMARY

Airborne radars to map inaccessible land masses are in almost constant use. However satellite borne radars have been limited to point to point distance and height measurement devices. The Geodetic requirement for contour mapping of the world oceans and the scientific requirement of contour mapping of remote planets have led to proposed satellite radar for these purposes.

This tutorial document reviews basic radar requirements for such missions. The concepts of pulse type radars when applied to satellite-to-planet geometry are not the same as when the radar to target distance is a few kilometers. However, if the differences are recognized, the radar properly designed, and the data system of sufficient capacity, contours of one (1) meter can be measured, sea states can be recognized and surface wind velocities over water can be determined. On the other hand the detection of ocean wave shapes, surface irregularities of less than a few centimeters, and small transient events require extremely accurate radars with per pulse errors less than one (1) meter. Conventional systems with extreme accuracies that qualify for space use may be in the future. However with the present day limitations of antenna size, realizable pulse lengths and satellite heights much of the desired information will have to be developed from return pulse shape study and analysis. To derive the desired information the transmitted pulse shape must be known, the effects of the receiver, detector and data systems upon the return pulse must be understood. This document explains some of these effects.

The effects of the reflecting surface upon the return pulse shape must be evaluated by in flight tests. The ability of a radar to determine altitude from the distorted return can only be determined by calibration of in flight equipment. These evaluations and calibrations will be conducted during the GEOS-C program.

SATELLITE ALTIMETRY

1.0 INTRODUCTION

Radar with its ability to penetrate clouds and accurately map contours is one of the few instruments which can be used to study the topography of a planet. Airborne radars have successfully mapped much of the terrain of planet earth. A space borne radar in the proper orbit could successfully complete the terrain mapping and also map the world oceans. Venus, our closest neighbor planet is still somewhat of a mystery. The reason – perpetual cloud cover. A properly designed radar placed in orbit around a planet could measure the vertical profile to an accuracy of several meters. The radar would weigh less than 100 pounds and operate at a wavelength of 15 centimeters or less. Shorter wavelengths can be used for higher resolving capability in earth orbit. However the "atmosphere" near Venus precludes the use of much shorter wavelengths. The choice of wavelength will be dictated by such features as planet atmosphere and desired resolving capability. The radar would determine the contour of the planet to be observed from an altitude of 1500 kilometers or less above the surface. A range tracking loop will be included for altitude tracking and this data used to improve the orbit determination around the planet under observation. Basically the orbit determination will be made using earth based tracking systems. The added parameter of vertical height above the planet should improve the orbit determination.

2.0 THEORY OF ALTITUDE DETERMINATION

The basic function of the satellite radar altimeter is to determine the height of the satellite relative to the subsatellite point on the planet. However due to surface irregularities the subsatellite point is not uniquely defined. To establish the physical interpretation of the height measurement, the subsatellite point is defined as the intersection of the spherical electromagnetic wavefront and a plane tangent to the planet at the nadir.

In Figure 1, the geometrical configuration of the satellite radar observations is illustrated. The satellite radar transmits a spherical shell (within the antenna beam) of radio energy whose thickness is the pulse length (τ) multiplied by the velocity of propagation (c) and the two-way propagation factor of one half. The spherical shell may be visualized as having a constant thickness of $c\tau/2$ independent of the radius of the sphere. The reflection of this spherical shell from the plane of the planet surface produces an inverted shell whose cross sectional radius increases with time and whose radar cross sectional area reaches a maximum when the trailing edge of the incident shell is tangent to the plane of the planet surface. After this maximum cross-sectional area has been attained the subsequent area responsible for reflecting radio energy takes the form of annular rings which are concentric with the initial area.

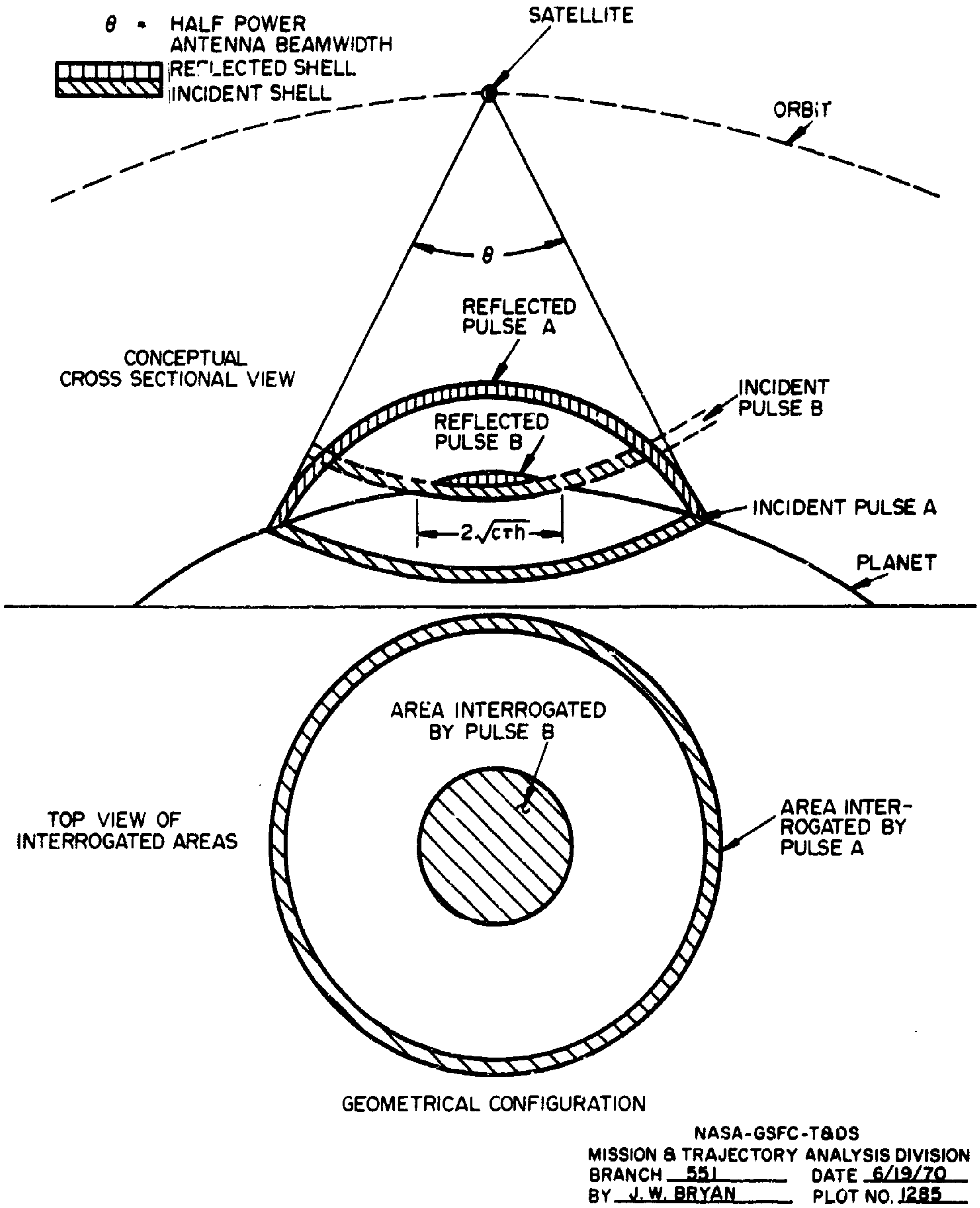


Figure 1. Geometrical configuration

For readily realizable antenna sizes, realistic pulse length and satellite height the initial reflecting disc will be much smaller than the disc subtended by the full antenna beam. Thus the angular resolution is determined by the radar pulse width and the system is pulse width limited. Thus the resolution is in the order of several minutes of arc for nominal orbit heights above the planet.

This high angular resolution permits the assumption of a plane surface for the planet reflecting area involved and leads to the following assumptions:

(1) all trigonometric functions of the angles involved may be equated to the angle

(2) the reflectivity of the interrogated surface is constant over the reflecting area on a per pulse basis

(3) the antenna gain is a constant and equal to the "on-axis" gain.

The first assumption results in the reflected spherical shell being converted to a conical shell which simplifies the analysis and does not affect the results. The second and third assumptions imply equal incident power and equal reflected power at all points within the interrogated surface.

2.1 RADAR EQUATION

The power received by the radar receiver is given by

$$P_r = \frac{P_t G^2 \lambda^2 \sigma^0 A}{(4 \pi)^3 h^4} \qquad (1)$$

where

P_r = received power per pulse

P_t = transmitter power per pulse

λ = operating electromagnetic wavelength

h = vertical height above the planet

σ^0 = reflectivity of the interrogated surface

A = reflecting area of the interrogated surface

As seen in Figure 1, the maximum reflecting area is $\pi c \tau h$ and is a function of time within the pulse where

$$A = \pi c h t_1 \quad 0 < t_1 < \tau^* \tag{2}$$

Substituting Equation 2 into 1, the received power

$$P_r = \frac{P_t G^2 \lambda^2 \sigma_0 c t_1}{64 \pi^2 h^3} \quad 0 < t_1 < \tau \tag{3}$$

As can be seen from Equation 3, for a constant height (h) the return pulse is a linear function of time up to the point $t_1 = \tau$. This is shown graphically in Figure 2 for vertical incidence. Equation 3 then represents the leading edge of the return pulse. It should be pointed out that Equation 3 and Figure 2 are idealized noiseless representations. The actual received pulse is noisy due to KT noise and expected surface variations in the order of the electromagnetic wavelength. The effects of surface variations upon the return pulse length has been treated by Professor Pierson[1].

* t_1 is measured from the on set of the return pulse and the transmitted pulse is rectangular.

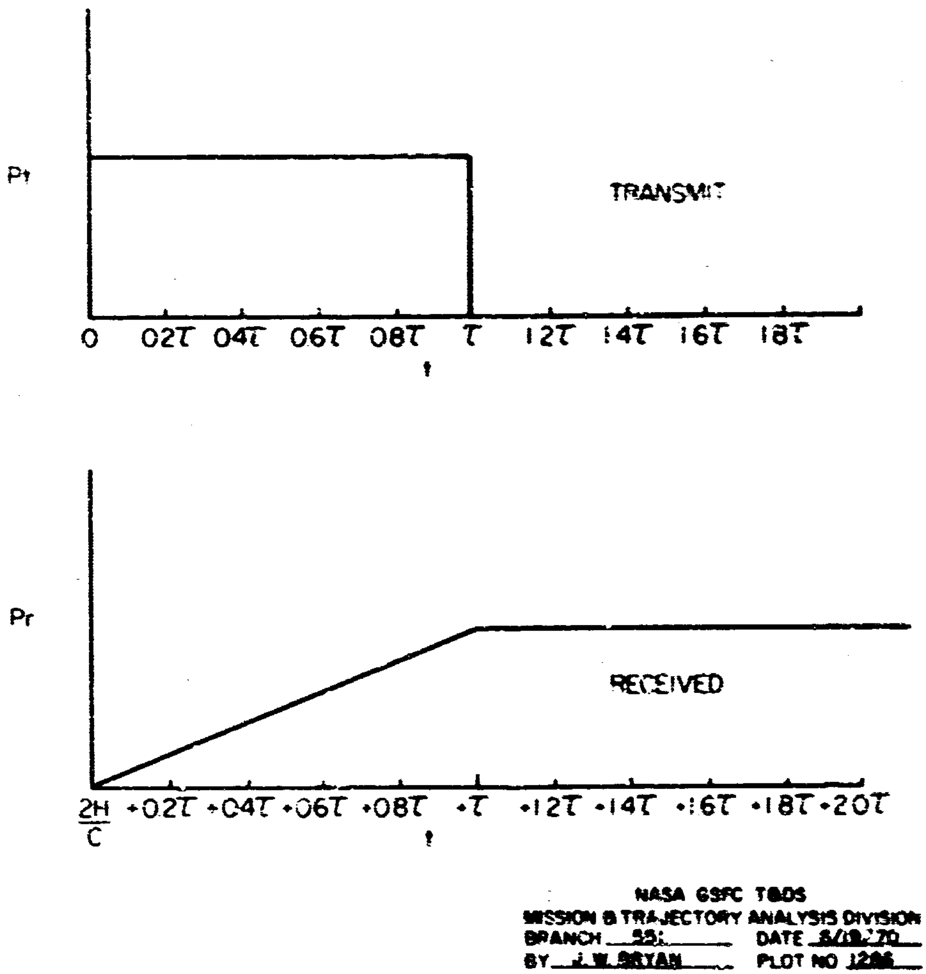


Figure 2. Idealized transmit and received altimeter pulse

2.2 EFFECT OF TRANSMITTER PULSE SHAPE

In the previous sections we have been dealing with an idealized rectangular transmitter pulse. Since practical systems have a finite rise time it is worthwhile to obtain some information regarding various transmitter pulse shapes. Equation 3 may be written in the form

$$P_r(t) = K_1 P_t(t) A \tag{4}$$

where K_1 includes all the constants of the system of Equation 3 and A is defined in Equation 2. For the given pulse width τ

$$P_r = A(t_1) \int_0^{\tau} K_1 P_t(t)\, dt \tag{5}$$

where t is measured from the onset of the received pulse. The received pulse powers as a function of time for several transmitter pulse shapes are shown in Figure 3.

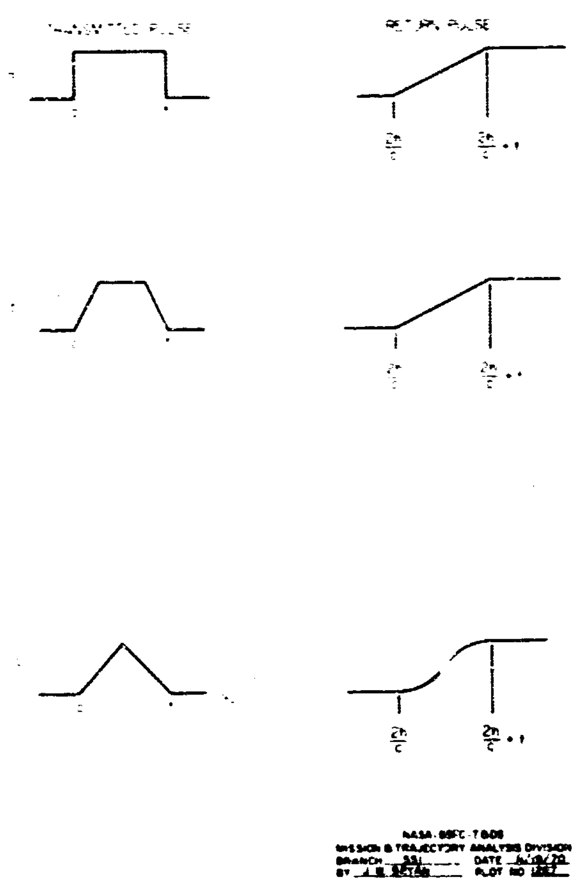


Figure 3. Average shape of ocean returns vs transmitted shape

The transmitter pulse shapes of Figure 3 are the idealized shapes. Practical circuitry prohibits vertical (zero time) rise and fall times as well as abrupt discontinuities. The output of a pulsed magnetron approaches 3a. The rise and fall times of a magnetron are limited by the cavity design and the electron density. Present state of the art magnetrons have rise and fall times in the order of a few (less than ten) nanoseconds

The use of extremely short pulse widths results in much the same problems whether a system uses pulse compression or a standard pulse system. It is not possible in a pulsed transmitter to generate an ideal Fourier spectrum that results in a prefect pulse in the time domain. Finite circuit passbands and nonlinear phase characteristics prevent time domain pulses from being uniformly treated in the frequency domain. Because of the wide frequency spectrum associated with short pulses the problem of generation and amplification is made difficult.

Early pulse compression systems achieved the goal of extremely short (approximately one nanosecond) pulses but they also generated discontinuities or side lobes. These side lobes were only 10 to 15 dB below main pulse. This limited the usefulness of the pulse compression systems for high resolution backscatter measurements. The echo from one scatter could easily be distorted by a side lobe from a second close by scatterer and there is no way to separate these pulses in amplitude or time.

Pulse shaping techniques, broadband circuitry and very linear phase responses have reduced the side lobe level in pulse compression system to resonable values.

With the advent of Traveling Wave Tubes (TWT) almost any pulse shape can be transmitted. However highly efficient, broadband (greater than 200 MHz) TWT's are at present beyond the state of the art. TWT's with greater than 1 GHz bandwidth are available "off the shelf" however the d.c. to r.f. efficiency of these tubes is low and none have been space qualified. TWT's have been built and effectively used in ground installations up to 500 kw output at X-band, however space qualified units are limited to one or two kilowatts and approximately 200 MHz bandwidths.

The availabilty of TWT's with at least moderate power and reasonable bandwidth allow one to consider pulse compression techniques (Section 3.0) for high resolution. Constant gain and linear phase over the bandpass are required of the transmitter in a pulse compression system.

2.3 RADAR RECEIVER

The leading edge or ramp of the received pulses directly affects the receiver design. A radar receiver will be considered as a bandpass filter having constant output to a detection device.

The receiver noise power (P_n) is expressed as KTB where K is Boltzmans constant, T the effective receiver temperature in degrees Kelvin and B is the

receiver noise bandwidth. The effective noise bandwidth of the receiver filter can be expressed as a constant times the half power (3 db) bandwidth; it also can be expressed as a constant times $1/\tau$. Except for a difference in the filter response the gain of the receiver is the same for both signal and noise.

The receiver filtering shapes the response to the average power return, limits the receiver noise power, and determines the natural frequency of the noisy variation about the average return. The receiver bandwidth must be at least as wide as the reciprocal of the pulse time to respond to the ramp type return defined previously. Bandwidths exactly this narrow however will alter the waveform and widening this bandwidth increases the noise power. A good compromise for the receiver bandwidth is still

$$B_n = \frac{1}{2\tau} \tag{6}$$

However, it must be recognized that this choice eliminates some of the information that could be obtained under high signal to noise ratios. The filter (receiver) bandwidth requirements for a pulse compression are based upon the dispersed pulse frequency spread. However, care must be exercised in the circuit design so that the gain and phase characteristics are linear or compensated.

2.3.1 Doppler Considerations

If the observing satellite is in a perfect circular orbit about a perfect spherical planet the frequency offset (Doppler) due to a change in height would

be neglected in the receiver design.* Eccentricity of the orbit results in a height change with time. This radial velocity results in a frequency offset (Doppler) which is readily calculated using the standard Doppler equation

$$f_d = f_t \left(1 - \frac{c - v_r}{c + v_r}\right) \tag{7}$$

where v_r is the rate of change of the height (h^0). This rate of change is determined by the orbit eccentricity and varies throughout the orbit. For a spherical planet

$$h^0 = e v \sin \psi \tag{8}$$

where e is the eccentricity, v is the velocity along the orbit and ψ is the positional angle with respect to the line of nodes at periapsis measured in the direction of the orbit. In a frequency coherent radar this frequency component is tracked out and the return signal is maintained centered in the i.f. filter. Early space borne altimeters cannot afford the weight and power required for the luxury of this circuit complexity, thus the receiver must be designed to accommodate a Doppler offset without causing the signal to stray into the filter skirts.

* Doppler differences from returns near the edge of the interrogated area do exist. But due to the small resolving area this component can be neglected for radars at 3 cm or greater wavelengths and nanosecond pulses.

2.3.2 Other Effects

Other factors also enter into the selection of the receiver bandwidth. Since the radar receiver will be of the heterodyning type, consideration must be given to the local oscillator frequency long term drift. (Short term drift or phase noise will be discussed later.) With the availability of state-of-the-art stable crystal oscillators this may not be a serious consideration. However, the stability requirement in light of the filter bandpass should not be neglected.

If the radar includes a pulsed magnetron, the frequency stability of the magnetron must be considered in the selection of the receiver bandpass characteristics.

When a radar antenna is scanned over several beamwidths or when the satellite attitude is not closely controlled, the received signal may be spread in frequency. This may be attributed to the amplitude modulation of the two-way signal as the addition of a velocity component since the radar no longer views vertically down. Steinberg developed an equation for this spectum spreading (σ) for a Moving Target Indicator (MTI) radar as

$$\sigma = \frac{\omega}{3.8\ \theta} \tag{9}$$

where θ is the beam width being scanned equal to 2 $\sqrt{c \tau h}$ and ω is the scan rate or is the attitude drift rate of the spacecraft.

2.4 DETECTION PROCESSER

As stated previously a coherent system is precluded as being too complex for the initial radar altimeters. Non-coherent detectors fall in two categories which describe the input-output characteristics of the mechanism. The linear detector can be described as having a linear relationship between input signal voltage and resulting detector output voltage. The rectangular transmitted pulse shown in Figure 2 is once again depicted in Figure 4, however the return pulse is now depicted as the output of a linear detector. It is noted that the rise is not linear yet still extends for the pulse period τ.

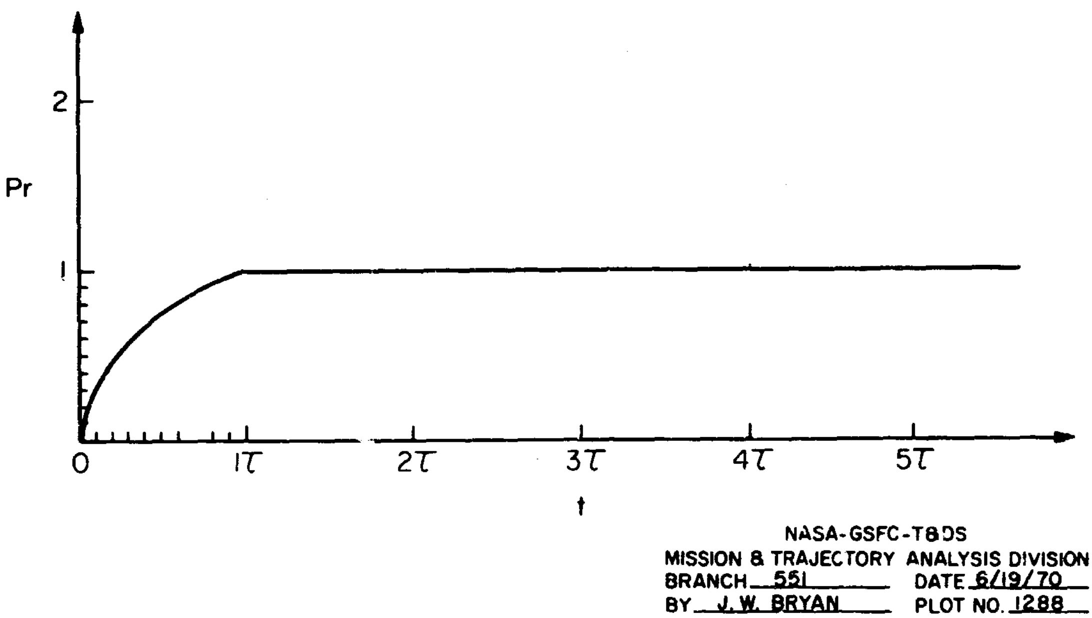


Figure 4. Characteristic radar altimeter return (envelope detection. AGC on return)

The square law detector is characterized by an output proportional to the input power. The return pulse indicated in Figure 2 is then a square law detector

output for a rectangular transmitted pulse. The returns depicted in Figure 3 may also be considered as outputs of square law detectors for the transmitter pulse shapes indicated.

In the pulse compression systems the detection process follows the compression network. Therefore the same detection criteria applies.

2.5 ALTITUDE DETERMINATION

For the unmanned satellite the on-board altimeter must contain some automated method of determining the radar range. The exact method of determination will be dictated by the measurement accuracy required and type of information desired. Also included in the altitude determination is the data transmission capability available.

The altitude (range) of the satellite above the surface of the planet is determined by measuring the two-way transit time of the electromagnetic energy.

$$R = \frac{c\ t}{2} \tag{10}$$

where R is the radar range or altitude

C is velocity of propagation

t is the two-way propagation time.

It is immediately seen that a quantization error of ±1 clock count must be applied to the altitude determination since

$$\Delta R = \frac{c\,\Delta t}{2} \tag{11}$$

where Δt is the clock interval.

Since the rise time of the transmitted pulse is several orders of magnitude smaller that the clock rate, the clock is usually started with the onset of the transmitter pulse with negligible error. The clock stop pulse is generated from the received pulse. For a noiseless system the clock could be stopped with the onset of the return pulse. However, systems are not noiseless. Several systems have been developed to determine a specific time associated with the noisy return pulse to generate the stop pulse.

The simplest form of altitude determination is perhaps the clock counter coupled with a threshold detection device. The clock counter is started by the onset of the transmitter pulse. The counter will continue to count clock cycles until a stop pulse is generated by the threshold detector. The threshold detector, if it were not for noise etc. on the return pulse, could be a biased diode which fired when the ramp of Figure 2 reached some fixed voltage. The firing of this diode would generate the stop pulse for the counter. Since the actual return is not as depicted in Figure 2 but rather a noisy version thereof, this threshold device would fire at random points in time. In actual practice some integrating could be done before the pulse was presented to the threshold device. This integrator could take the form of a bandpass filter whose passband will not

allow for changes of slope at a rapid rate. However small changes in altitude will be masked by this technique. In fact, any form of averaging or integration will mask or average out small altitude changes. This filter could also be of the form of a low pass post detection filter. However, some of the effect of noise biasing of the detector is eliminated using pre-detection bandpass filtering.

A second method of determining the time to generate the stop pulse is the delay differencing technique. Referring to Figure 5, the received pulse is split into two paths. The time delay in path (b) is made exactly (τ) longer than path (a). The two-signals are then subtracted giving the power pulse of Figure 5b. The peak of this pulse is then used to generate the clock stop pulse and the time to be inserted in Equation 10 is

$$t = t_c - \frac{\tau}{2}$$

where t_c is the clock counted interval.

It is immediately apparent that a time jitter due to noise on the return will also affect the accuracy of this system.

There exist other techniques for developing a pulse to stop the clock counter. Descriptions of these systems are available in the various radar system manuals.

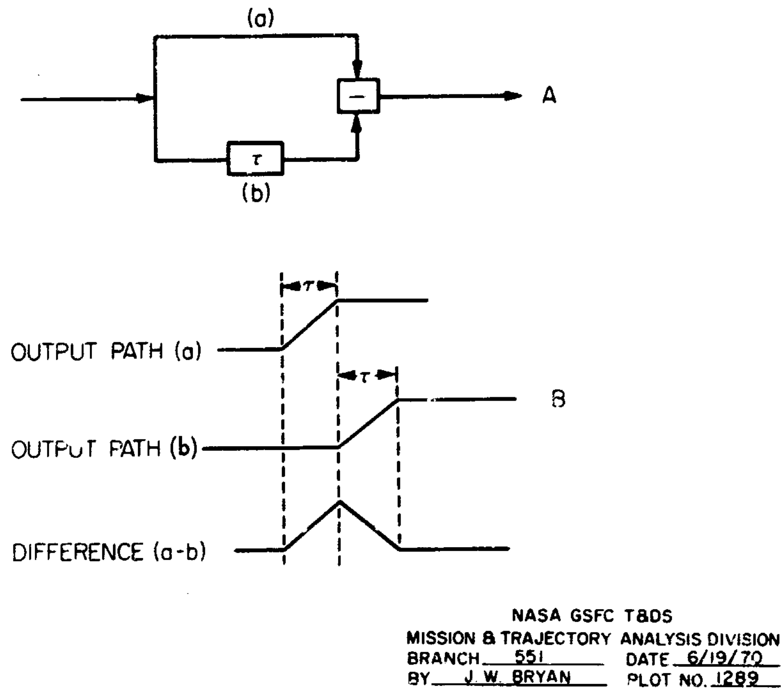


Figure 5. Delay differencing

2.6 RETURN PULSE CONSIDERATIONS

In order to design a radar for height measurements the mecnanism of the diffuse reflectors must be understood. In operation over a rough surface the return pulse is the resultant of reflections from all elements within the resolution area.[3] Since the return from such a surface is a function of wavelength, pulse length, polarization, height of surface irregularities, and reflection coefficient, the radar return is complex. If the resolution area contains many contours which are larger than a wavelength the return may be considered to be from scatterers uniformly distributed over the area. In this case, the quantity (σ^0) termed the "radar cross-section per unit area" is used and is independent of

most of the radar parameters.[4] Grant and Yaplee obtained data that indicated that (σ^0) was approximately proportional to the square of the frequency for sea and land returns.

The backscattering characteristics or realistically the value of (σ^0) when the interrogating source is a satellite is one of the objectives of current altimeter programs. Values currently being used in radar designs vary from +20 dB for relatively calm (10 knot winds) seas to zero dB for the planet Venus to -25 dB for tree covered terrain. A conservative value for the world ocean is +6 dB, while the reflection measurements at the Jet Propulsion Lab (JPL) reported by Carpenter[5] indicate a reflectivity of +4 dB for Venus at vertical incidence and dropping sharply to -30 dB at 60° off vertical.

A few generalizing statements are appropriate to indicate the nature of the scattering process. Goldstein[6] reported that a steady reflection from the earth's terrain could be attributed to the reflections from elements that moved $\lambda/4$ or less. He found little scintillation from a wooded area at wind speeds below approximately 12 knots. Above 12 knots the return distribution followed a Rayleigh distribution for random scatterers. Grant and Yaplee[4] showed that the value σ^0 is almost independent of angle of incidence when the interrogated terrain is covered with tall growth (trees, etc.) and this is also applicable to rocky terrain. The values developed by Grant and Yaplee have been accepted and used when no specific data exists. It is expected that these values should be used for the reflectivity of other planets until more specific data can be obtained. The

value of σ^0 for the open oceans of the world is quite variable and dependent upon the roughness of the water. The actual value has been determined from aircraft calculations by many observers. Samples of the published curves are shown in Figure 6 for the various wind speeds. These values must be verified when the interrogating source is a satellite altimeter, however, they should be used as design criteria.

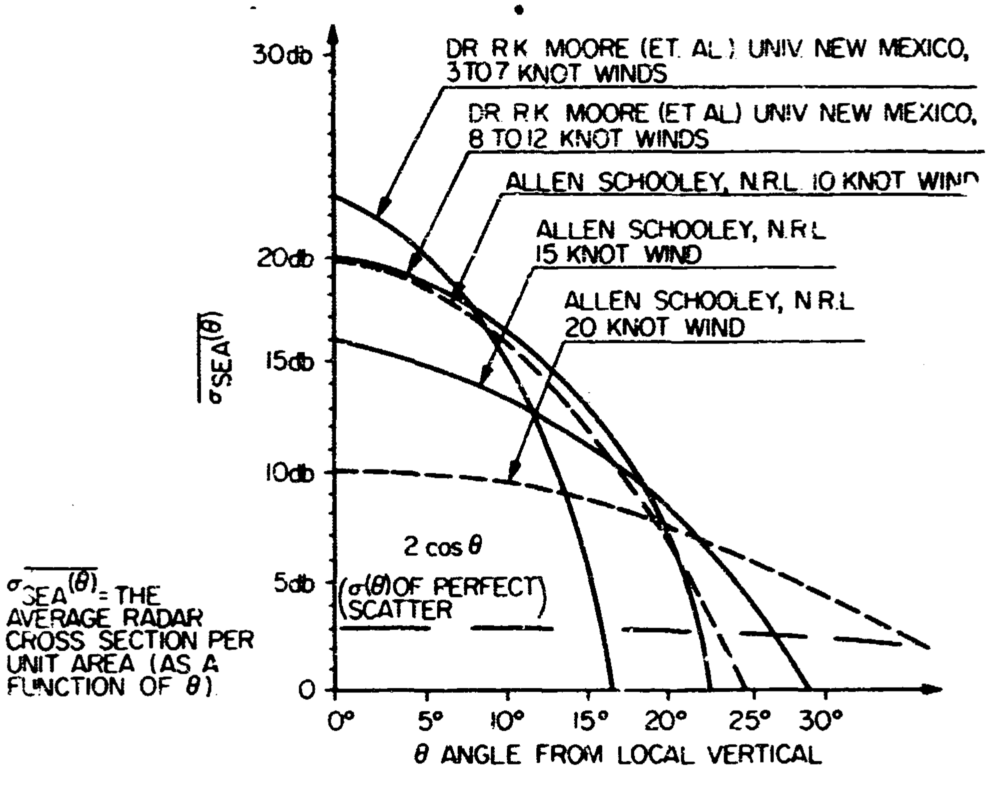


Figure 6. Radar cross section vs incident angle reproduced from ref. 13

The reports of Katzin[3] and Goldstein[6] indicated that knowledge of the small surface irregulaties can be gained from studies of the individual return pulse shapes. The effect upon the slope of the leading edge of the return pulse has been studied in reference 1. Since the entire return pulse is the sum of the return from many small reflectors, some information regarding the size and spacing of these reflectors can be assertained if the reflecting surface is viewed from an angle. For a static surface such as a non fluid planet or land return the same surface can be viewed from several angles and subsequent orbital passes or the antenna may be scanned during any one pass.

This corresponds to the side looking or forward looking radars presently used for aircraft mapping. To gain the desired information the entire return pulse or pulses must be available. To this end the entire radar return must be sampled and telemetered to the earth. The number of samples required depends upon the amount of information desired, the radar system resoltuion and the scan rate of the system. The orbital motion of the spacecraft is considered as a scan. It is not necessary to sample the return for the entire Prf period. The sampling period can be adjusted automatically by the altitude tracking system and the period of sampling designed to sample only the portion of the return desired for study.

The design of a side looking or scanning radar mapper must consider the variation of σ^0 with look angle and the effective footprint or shape of the

interrogated area. R. H. Laprade describes the radar mapper as applies to aircraft in reference 8. Care must be exercised in applying this description to relate all parameters to satellite application.

2.7 DATA SYSTEMS CONSIDERATIONS

The ability to command the tracking gates to a close approximation of the correct tracking time will be required. This will alleviate many of the design constraints on the tracking loop when in the search mode. Without this capability, the tracking loop must search over an entire Prf interval. The altimeter should be designed with a search and acquisition mode. In this mode, the radar could transmit a rather long (1 μ sec or longer) pulse. As seen in equation 3 the received power is a direct function of the pulse length. By transmitting a long pulse and receiving the high signal-to-noise ratio the acquisition process is made easier. With this high SNR and the tracking gates commanded to a narrow search range acquisition should be accomplished in tenths of a second.

Some "on-board" processing of the altitude determination must be included in the initial design. No data will normally be extracted from the altimeter until the tracking gate is locked to the return pulse. As indicated previously, the effect of noise either receiver (internal) or received (external) will be to cause the tracking mechanism to jitter about the correct tracking point. These noise variations will be integrated out onboard over a relatively long interval. This

exact interval is a function of the desired resolution, orbit eccentricity and the speed of the subsatellite point over the surface of the planet. An altimeter with tenths of a meter accuracy does not give definitive information if the measurement is average over terrain which has varied several meters during the averaging period. Thus some idea of the contours to be mapped must be factored into the "on-board" processing. In mapping the mean sea level of the world oceans the individual wave heights can and should be averaged out. However, in determining fine grain contours such as the sea state of the ocean the individual wave height must be measured. Since little is known of the surface contours of the various planets the initial contour mapping radars will not be high resolution but rather have 20 to 50 meters resolution. With this coarser resolution longer averaging periods can be tolerated. After the coarse contours of a planet have been mapped and analyzed the finer grain structure of the surface can be mapped on subsequent flights.

The availability of data links must be examined in relation to the radar resolution. It may be necessary to obtain and store data at a relatively high rate for playback at a lower rate. With the advent of Data Relay Satellites this storage and playback may not be necessary for earth orbiting radars as real time high data rate channels will be available.

The data processing system of any radar altimeter will depend upon several basic radar parameters: 1) type of detection process, 2) type of tracking process,

3) filtering techniques, 4) signal-to-noise ratio, 5) ultimate resolution desired. Each of these parameters has been discussed previously in relation to the radar. They will now be discussed in relation to the data processing systems.

In the non-coherent system discussed in this paper no attempt is made to correlate the phases and frequencies of the transmitted and received signals. Signal returns from each pulse are detected separately and averaged together after detection (post detection integration). The block diagram of such a system is shown in Figure 7.

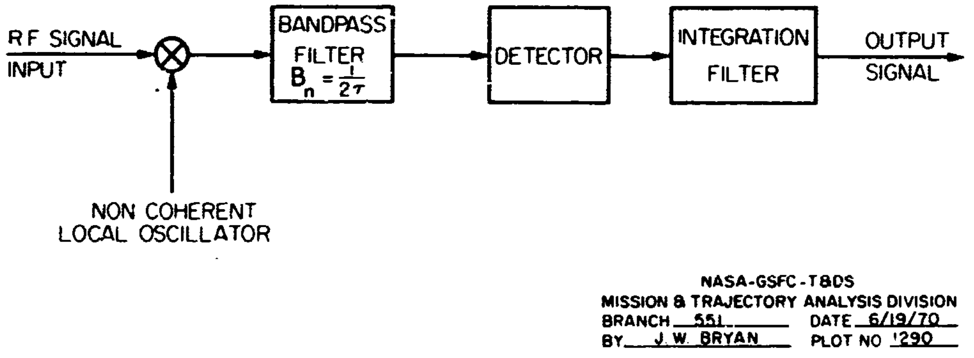


Figure 7. Non coherent detection and integration diagram

As shown by Barton[9] this improves the signal-to-noise ratio of the output signal by a factor of n^{α}, where (n) is the number of returns integrated and (α) may be between 0.5 and 1.0. For low signal-to-noise ratio (α) is taken to be 0.5 and for high signal-to-noise ratio (α) is taken as 1.0. In the initial design of a radar (α) is usually assumed to be 0.6. Thus non-coherent integration does not

make optimum use of the system information, however, in the early stage of satellite altimetry the complexity versus optimization seems to indicate the less complex system.

It should be noted at this time that any system losses must be included in arriving at the signal-to-noise ratio into and out of the integrating filter. The improvement factor (n^{α}) does not include any of these losses.

An important factor to be considered in integrating several return pulses in an effort to improve the signal-to-noise ratio for altitude determination is the correlation of the surface noise. The sea (for example) at any particular point is ever changing, but during the observation time of a high p.r.f. satellite altimeter the sea is essentially frozen in position. Thus the surface clutter or noise will tend to correlate from pulse to pulse throughout the integrating period and the integration does not necessarily improve the signal to clutter ratio as happens in the case of uncorrelated noise. The decorrelation time of sea clutter is stated by Croney[10] to be about 0.01 seconds at X-band frequencies.

The correlation of the surface clutter on a pulse to pulse basis may well prove an advantage when the return pulse is being sampled for surface roughness studies.

2.8 ALTIMETER RESOLUTION

The ability of the radar altimeter to accurately determine the vertical height variations above the sub orbital point is a function of the pulse length, operating frequency and range determination system. The system will never be able to resolve variations less than one-half the operating wavelength. The range resolution of the beamwidth limited radar is defined by the pulse length and the net signal-to-noise ratio. For a leading edge tracker, Skoinik[11] defines the range resolution as

$$\delta T_R = \left(\frac{\tau}{2\,BE/N_0}\right)^{1/2} \tag{12}$$

where

$T = 2R/C$

τ = pulse height

B = receiver noise bandwidth

E = signal energy

N_0 = noise power per unit bandwidth

for a transmitted pulse having a vertical (zero rise time) leading edge. Equation 12 should be directly applicable to the satellite altimeter.

3.0 PULSE COMPRESSION

The information in the previous sections as regards detection and data processing apply equally well to pulse type and pulse compression systems. In

general pulse expansion and compression networks in the transmitter and broadband receiver respectively will deliver the same signal to the measurement circuitry as a short high amplitude pulse system. Pulse compressions system may be arbitrarily divided into two classes, a) passive pulse compression, and b) active pulse compression. Both methods are used in present day airborne systems and could be implemented for space use.

3.1 PASSIVE PULSE COMPRESSION

The passive pulse compression system is characterized by operating upon the signal in a coherent manner and thus increase the resulting signal-to-noise ratio. A simplified system is illustrated in the following way. The transmitter pulse is swept in frequency during the time of transmission. Ideally this sweep would be linear with time. The received pulse is passed through a dispersive network whose delay versus frequency follows exactly the transmitter sweep but with a reverse spectrum. This may be seen in Figure 8.

A second illustration is given in Figure 9. A spike of r.f. energy is generated by discharging an energy storage device such as avalanching a diode in a cavity. This spike is fed to a dispersive delay where the various frequency components of the energy spike are delayed according to the delay versus frequency characteristics of the network. This decompressed pulse is then transmitted. The return pulse is fed through the same dispersive network, after reversing the spectrum, and ideally the original spike is obtained. There are

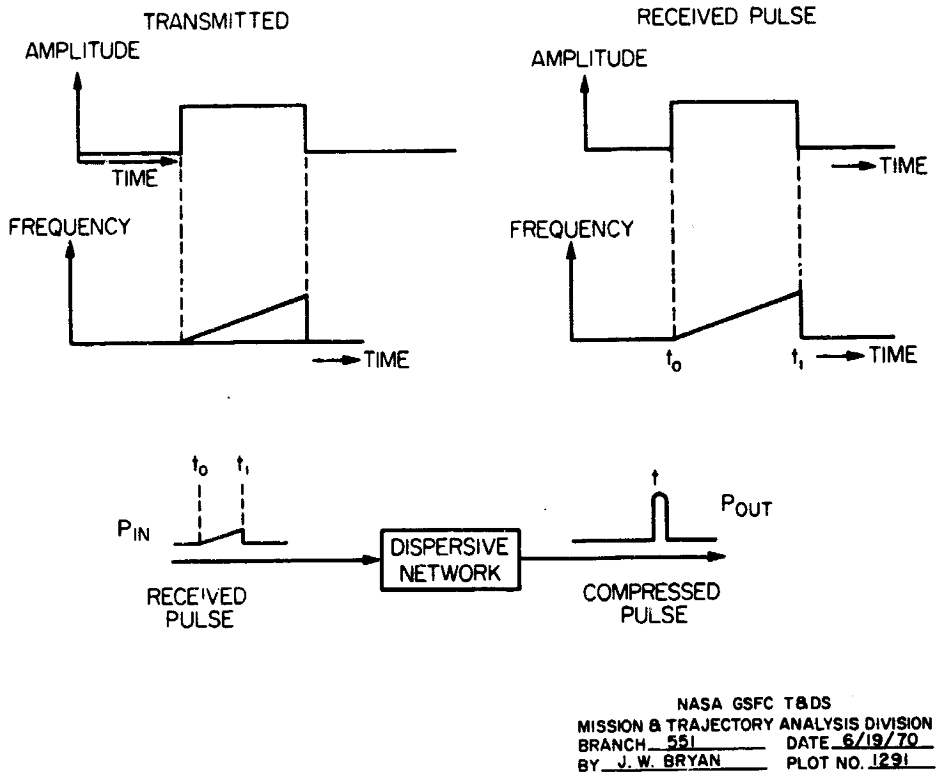
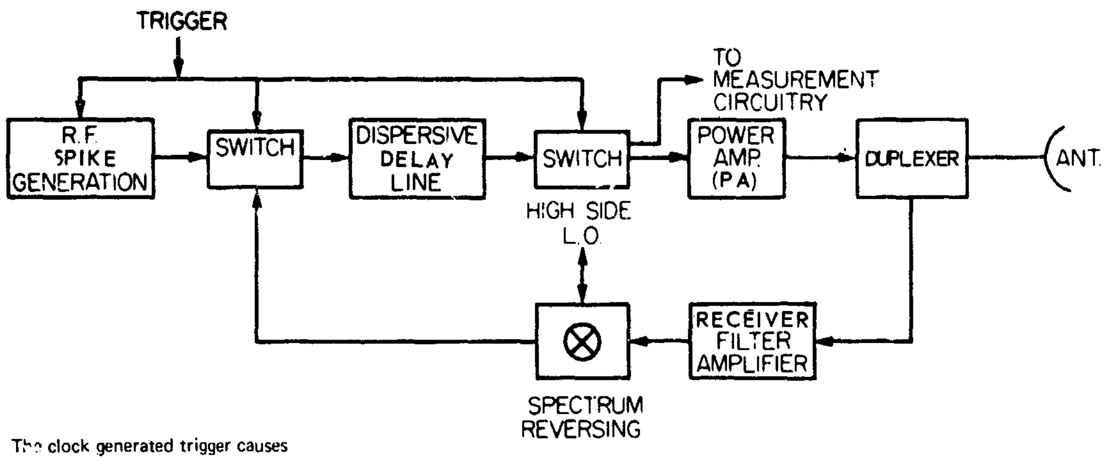


Figure 8. Chirp system pulse shapes

various other spectrum generating and collapsing methods which have been demonstrated successfully in ground based system. Most of these, however, require some manual sweep adjustments for correlation which are deemed too complex for the state-of-the-art in automated spacecraft.

3.2 ACTIVE PULSE COMPRESSION

The active pulse compression system is characterized by narrowband filtering of the noise to enhance the signal-to-noise ratio. An explanation of this method is as follows.



The clock generated trigger causes

1) a spike of r.f. energy to be generated
2) the delay line to be connected to the spike generator
3) the output of the delay line to be fed to the P.A.

to happen simultaneously. At the end of the spread r.f. pulse the switches connect the delay line into the received signal path.

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MISSION & TRAJECTORY ANALYSIS DIVISION
BRANCH 551 DATE 6/19/70
BY J. W. BRYAN PLOT NO. 1292

Figure 9. Pulse decompression/compression diagram

The transmitted pulse is once again swept in frequency during transmission. However, the linearity or matched filter is not required. A replica of this swept frequency is used as the heterodyning oscillator in the receiver. This receiver sweep is offset slightly in time from the received signal resulting in a C. W. tone during the pulse. This C. W. tone may now be passed through a narrowband filter and thus the noise reduced increasing the signal-to-noise ratio.

4.0 SUMMARY

The actual design parameters of a satellite altimeter are dictated by the orbital elements, the type of surface to be mapped, the resolution desired, and the physical constraints of size, weight, and power placed upon the design by the

spacecraft. The radar altimeter design properties are summarized in Table I. Each of these properties may have different scientific applications. A single radar may be designed to supply any or all of those listed, however the complexity of such a radar may exclude some types from an automated spacecraft. The

Table I

Radar Return Information

Basic Property	Major Dependency	Desired Information
Time Delay	Distance from radar to surface	a) topographic map b) orbit determination
Doppler Shift	Velocity with respect to surface	a) horizontal motion (v) b) vertical motion ($\dot{h}$) c) eccentricity
Pulse Shape	Surface roughness of interrogated area	a) slopes b) sea state c) minor surface perturbation
Pulse intensity	Reflectivity Geometry	a) surface content b) surface shape
Depolarization	Surface roughness	a) Brewster angle b) specular or diffuse reflection

required storage or telemetry capability for pulse shape studies may be very high. Depending on the detail desired, a single radar pulse may require up to ten

samples of five bits per sample. At a pulse repetition rate of one thousand pps this means 50 K bits per second of data.

5.0 PREVIOUS EXPERIENCES

Radar altimeters have been flown on several space programs, however their prime determination was limited to altitude and rate of ascent or descent. The "Surveyor" spacecraft employed a CW altimeter system using two orthogonal antenna arrays to supply not only descent rate but also a velocity over the surface component.

The Saturn launch vehicle electronics also includes an altimeter. This is limited to a height determination alone. This system is a pulsed radar ranging unit with a 15 meter accuracy. The antenna for this altimeter is a slotted array mounted in the side of the vehicle. The maximum design range of 300 nm of unambiguous altitude has been achieved on all Saturn flights.

The Lunar Excursion Module (LEM) of the Manned Space Flight Program uses a landing radar similar to the Surveyor radar in that altitude and velocity are determined by CW system. The descent and horizontal velocities are determined using three separate r.f. beams radiating at a slight angle to the spacecraft axis. The altitude is determined using an FM/CW system with its own axial r.f. beam. This system is designed to operate from an altitude of 50,000 ft. to

touchdown. A description of a range-Doppler measuring pulse compression radar is given in Reference 12. That system was placed in operation in 1962 for special missile measurements.

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